THE UNIVERSITY OF BRITISH COLUMBIA

ELECTRONICS II

ELEC 301

MINI PROJECT 2

AUTHOR: TRAVIS INNES

STUDENT NUMBER: 28564383

PREPARED FOR: DR. NICOLAS JAEGER

March 3rd, 2024

Contents

1 Objectives

To develop familiarity with the transistor's hybrid-pi model and issues surrounding the biassing of transistors as well as to analyse and measure the characteristics of an important transistor amplifier using 3 commonly available transistors.

2 Part I: Methods of Simulating DC Operating Point

2.a 2N2222A Small Signal Parameters from Datasheet

Extracting the small signal h-parameters for 2N2222A at $V_{CE} = 10V,\ I_C = 1mA,\ f = 1kHz,\ and\ T = 25C$. Taken from 2N2222A datasheet.

H-Parameters	Min	Max
H_{fe} (Small Signal Current Gain β)	50	300
H_{ie} (Input Impedance r_π)	$2k\Omega$	$8k\Omega$
H_{oe} (Output Admittance $1/r_o$)	$5\mu S$	$35\mu S$

Table 2.1: Small Signal H-Parameters

2.b Comparing Simulation to Datasheet

Below we will simulate and graph the response of the 2N2222A. We will deduce variables g_m, R_π, β, r_o, and V_A given I_b= 1mA and V_{CE} = 5V and compare it to the expected output from Table 2.1.

2.b.1 Plotting for I_b vs V_{BE}

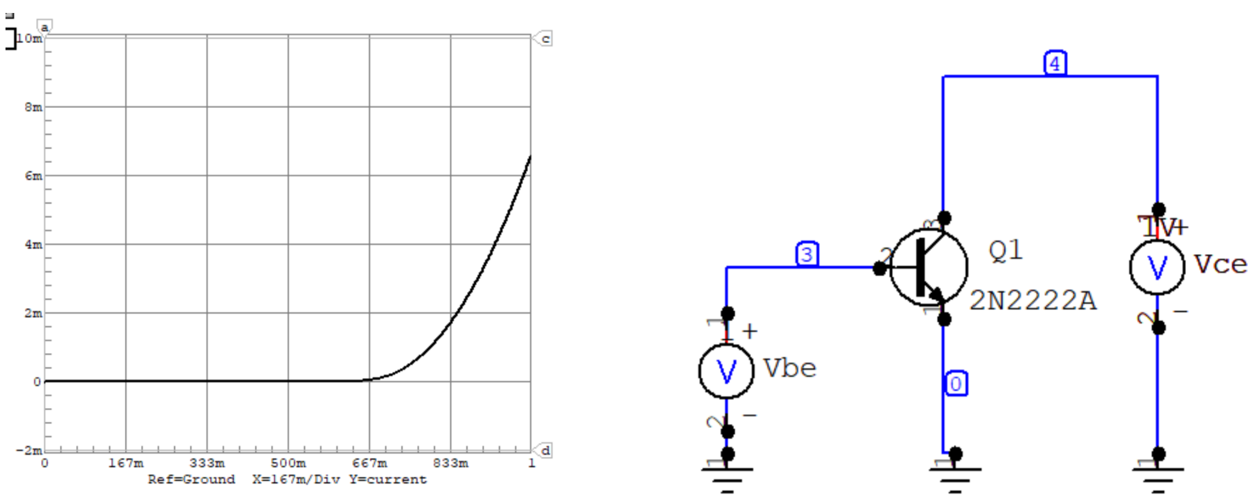

Figure 2.1: I_b vs V_{BE}

2.b.2 Plotting for I_c vs V_{CE}

The graph below shows a DC sweep on V_{CE} from 0-10V in increments of 10mV and will help us find Beta. From the data sheet we know beta is anywhere from 50-300, knowing a beta of 100 is common we will use that to center our I_B parameter on. When beta is 100 I_B is 10uA. So we will sweep from 5uA-15uA in increments of 1uA. Below we can see at 5V and 1mA we center on our 2nd I_B sweep which corresponds to $\boxed{I_B = 6\text{uA}}$.

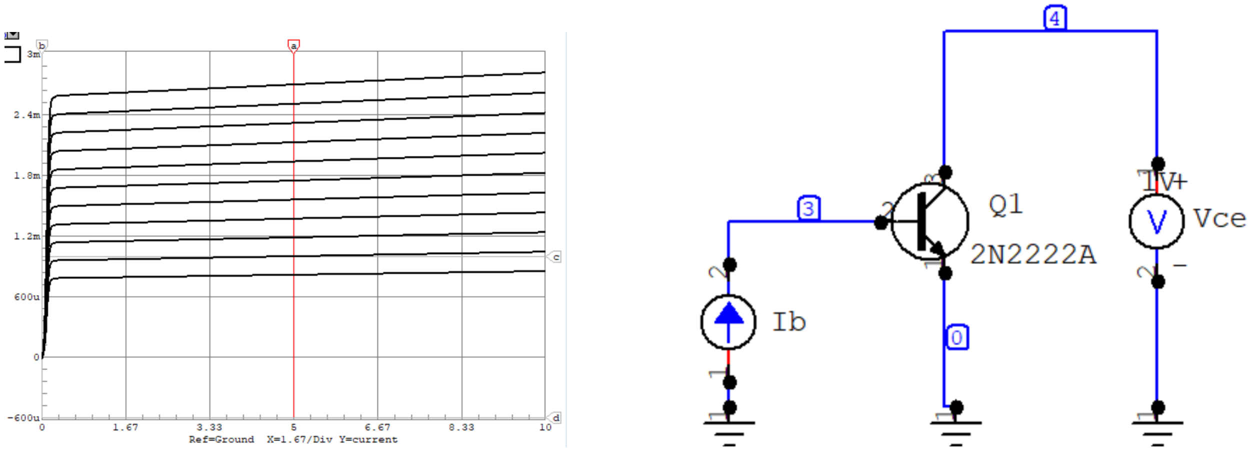

Figure 2.2: I_c vs V_{CE} with I_B as the variable parameter

2.b.3 Plotting for I_c vs V_{CE}

The graph below shows a DC sweep on V_{CE} from 0-10V in increments of 10mV, and V_{BE} from 0.6-0.7V in increments of 10mV.

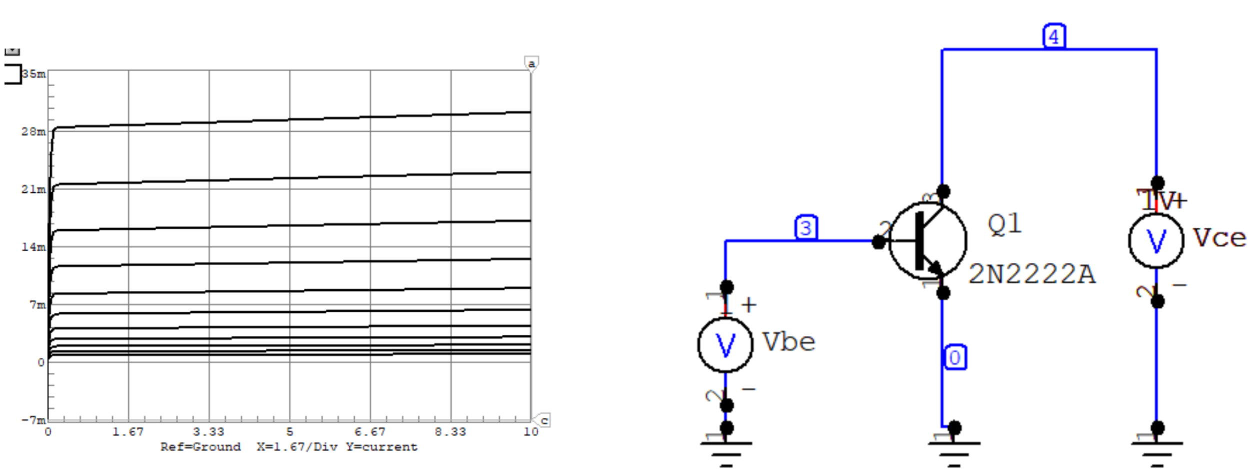

Figure 2.3: I_c vs V_{CE} with V_{BE} as the variable parameter

2.b.4 Bringing it together

Given from Ic = 1mA, V_{CE} = 5V, and from Figure 2.2 where we conclude I_B

$$g_m = \frac{I_C}{V_T} = \frac{1mA}{25mV} = \boxed{0.04\text{S}} \quad r_\pi = \frac{\beta}{g_m} = \frac{166.67}{0.04S} = \boxed{4.17\text{k}} \quad \beta = \frac{I_C}{I_B} = \frac{1mA}{6uA} = \boxed{166.67}$$

From Figure 2.3 can we extrapolate the Early voltage V_A from the graph by using the existing slope and derive r_o.

$$y = m * x + b \quad \rightarrow \quad 0 = \frac{1.681m}{9.214} * V_A + 28.42m \quad \rightarrow \quad Va = \boxed{155.78}$$

$$r_o = \frac{V_A}{I_C} = \frac{155.78}{1mA} = \boxed{155.78k\Omega} \quad \frac{1}{r_o} = \frac{1}{155.78k\Omega} = \boxed{6.41uS}$$

Comparing our simulated values to our Datasheet values:

H-Parameters	Min	Max	Simulated
H_{fe} (Small Signal Current Gain β)	50	300	166.67
H_{ie} (Input Impedance r_π)	$2k\Omega$	$8k\Omega$	4.17kΩ
H_{oe} (Output Admittance $1/r_o$)	$5\mu S$	$35\mu S$	$6.41\mu S$

Table 2.2: Small Signal H-Parameters vs Simulated Parameters

Given our values fall between the expected min/max we see that they are reasonable. We now have extracted usable parameters which we can use to find our DC operating point.

2.c Finding The DC Operating Point

We use 3 different methods below to solve the bias circuit in Figure 2.4 to find the DC operating point. Firstly, we will solve for R_{B1}, R_{B2}, R_C, and R_E given we know V_{CC} = 15V and I_C = 1mA. Then find and compare DC operating points.

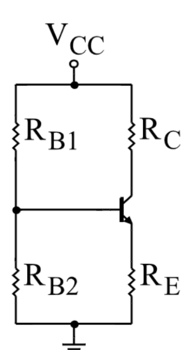

Figure 2.4: Simple Bias Network Circuit

2.c.1 Using Simulated Paramters From Above

From our simulated parameters above we know I_C and I_E. For the 2N2222A transistor to bias we want a V_{CE} of 4V or less and for $R_E = R_C/2$. So we can solve for R_E and R_C.

$$V_{CC} = (2 * R_E) * I_C + 4V + R_E * I_E \quad \rightarrow \quad \boxed{\mathrm{R}_E = 3.67k\Omega} \quad \boxed{\mathrm{R}_C = 7.33k\Omega}$$

Transforming our bias circuit into a single mesh we can use the following equations to solve for R_{B1} and R_{B2}.

$$\text{(eq.1) } V_{BB} = I_B * R_{BB} + V_{BE} + R_E * I_E \quad \rightarrow \quad V_{CC} * \frac{R_{B2}}{R_{B2}+R_{B1}} = I_B * \frac{R_{B2}}{R_{B2}+R_{B1}} + 0.7 + R_E * I_E$$

$$\text{(eq.2) } I_2 = I_1 + I_B \quad \rightarrow \quad \frac{R_E * I_E + 0.7}{R_{B2}} = \frac{V_{CC} - V_B}{R_{B1}} - I_B$$

Solving the system of equations eq.1 and eq.2 find that the resistors R_{B1} : R_{B2} are related by a ratio of 1:0.41. $\boxed{R_{B1} : R_{B2} = 1{:}0.41}$. We will use this when we compare the three methods to choose a pair of resistors that make sense given we want a VBE below 4V.

2.c.2 Using 1/3 Rule

I will use the second method of the 1/3 rule. We know I_C, V_{CC}, V_B, V_C, V_E, β, and I_1 so we can immediately solve for R_C, R_E, R_{B1}, and R_{B2}.

$$R_C = \frac{V_{CC} - V_C}{I_C} = \frac{5V}{1mA} = \boxed{5k\Omega} \qquad R_E = \frac{V_E}{I_E} = \frac{5V}{1mA} = \boxed{5k\Omega}$$

$$I_1 = \frac{I_C}{\sqrt{(\beta)}} = \frac{1mA}{\sqrt{(166.67)}} = 77.62uA \qquad I_2 = I_1 - I_B = 77.62uA - \frac{1mA}{166.67} = 71.59uA$$

$$R_{B1} = \frac{V_{CC} - V_B}{I_1} = \frac{15 - 5.7}{77.62uA} = \boxed{119.82k\Omega} \qquad R_{B2} = \frac{V_B}{I_2} = \frac{5.7}{71.59uA} = \boxed{79.62k\Omega}$$

2.c.3 Using 1/3 Rule and Available Resistors

The closest standard resistors for R_C, R_E, R_{B1}, and R_{B2} based on our calculated values.

$$5k\Omega \rightarrow \boxed{5.1k\Omega} \qquad 119.82k\Omega \rightarrow \boxed{120k\Omega} \qquad 79.62k\Omega \rightarrow \boxed{82k\Omega}$$

2.c.4 Comparing the 3 Methods

Using our resistances found from simulating as well our resistances found from using the 1/3 rule we can find and compare our estimated DC operating points for the given methods. Recalling back to 2.c.1 we deduced a relationship between R_{B1} and R_{B2}, namely R_{B1} : R_{B2} = 1:0.41. I have used 10k and 4.1k which keeps our transistor biased.

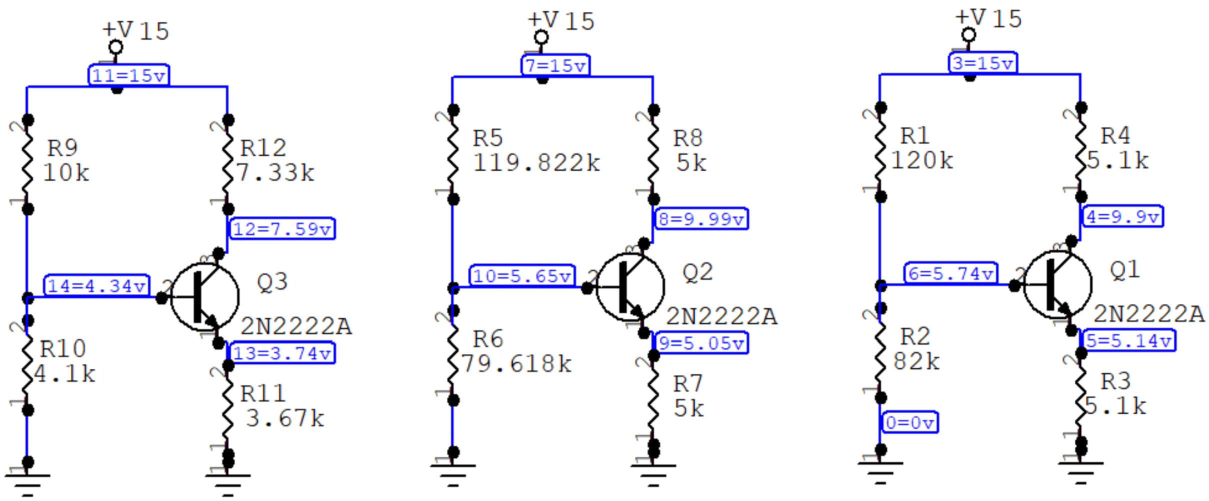

Figure 2.5: Simple Bias DC Operating Points

Methods	V_C	V_B	V_E	I_C	I_B	I_E
Simulation	7.59V	4.34V	3.74V	1.01mA	6.11uA	1.02mA
1/3 Rule	9.99V	5.65V	5.05V	1.00mA	6.05uA	1.01mA
1/3 Rule with Standard Resistances	9.90V	5.74V	5.14V	1.00mA	6.03uA	1.01mA

Table 2.3: Simple Bias DC Operating Points

We see that all methods are successful at biasing the transistor. Specifically going from the 1/3 rule to the 1/3 with standard resistors, we see the difference is negligible so it should always be a safe bet to use standard resistors. All methods see nearly the same currents through the transistor with slightly varying voltages

2.d DC Operating Points of Alternate Transistors

To check the robustness of our 2.c.3 solution we will compare the result when applied to other transistors. Here we compare 2N2222A with 2N3904 and 2N4401. What we find is nearly identical results for their DC operating points. There is however a noticeable change in V_{BE} drop. 2N2222A with a V_{BE} of 0.6V, 2N3904 with a V_{BE} of 0.65V, 2N4401 with a V_{BE} of 0.75V.

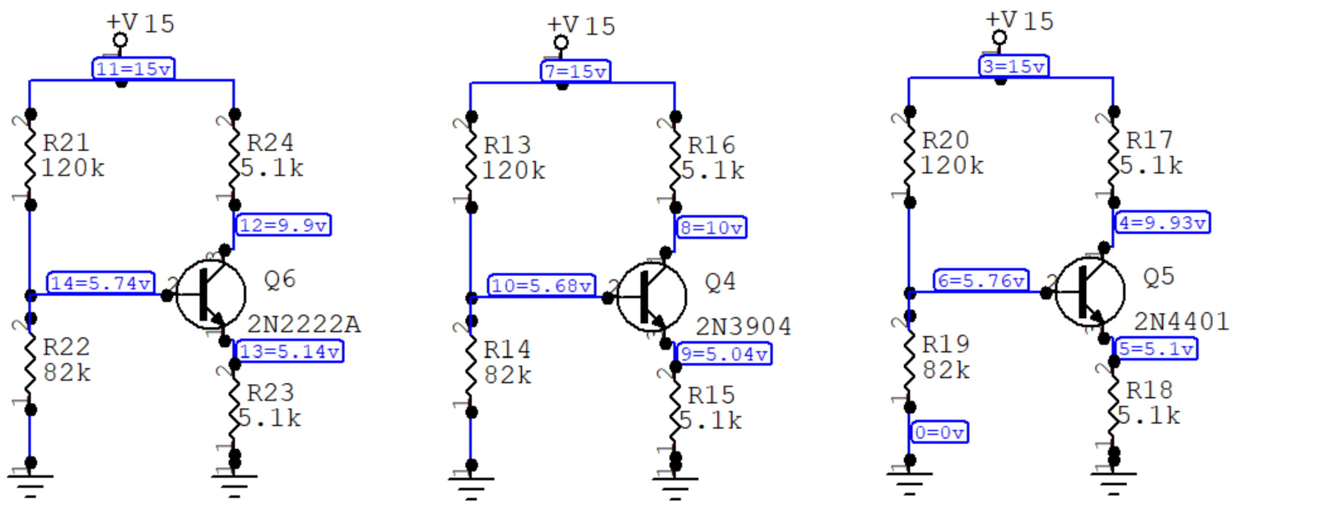

Figure 2.6: Simple Bias DC Operating Points: Differing Transistors

Transistors: Using Method from 2.c.3	V_C	V_B	V_E	I_C	I_B	I_E
2N2222A	9.90V	5.74V	5.14V	1.00mA	6.03uA	1.01mA
2N3904	10.00V	5.68V	5.04V	0.99mA	5.93uA	0.99mA
2N4401	9.93V	5.76V	5.10V	0.99mA	5.98uA	1.00mA

Table 2.4: Simple Bias DC Operating Points: Differing Transistors

3 Part II: The Common Emitter (CE) Amplifier

3.a Calculating vs Approximation Methods: Comparing Poles/Zeros

APPROXIMATION METHOD:
First we simulate and approximate the differences using both 2N4401 and 2N3904.

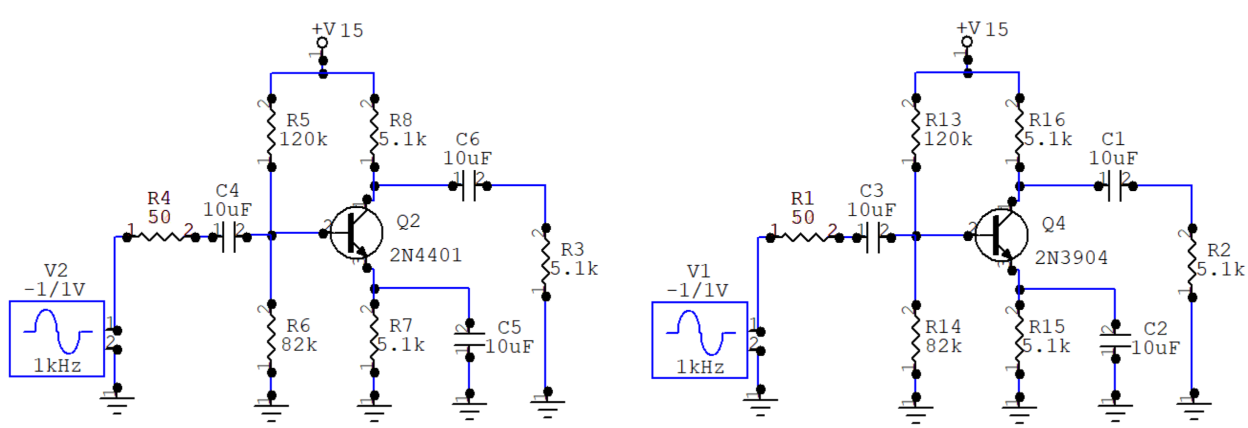

Figure 3.1: 2N4401 (left) and 2N3904 (right) CE Amplifier

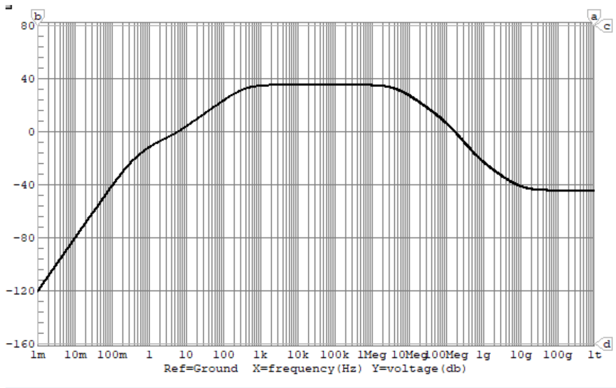

Figure 3.2: 2N4401 (left) and 2N3904 (right) CE Amplifier Bode Magnitude Plots

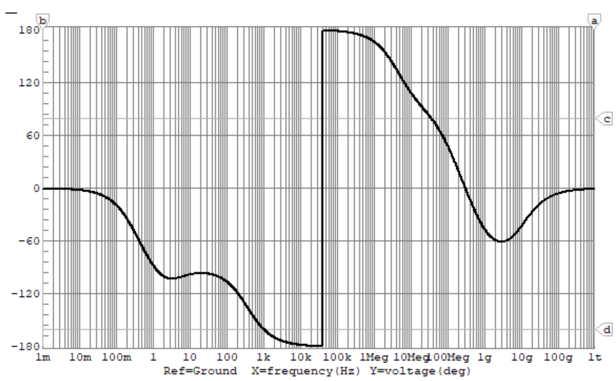

Figure 3.3: 2N4401 (left) and 2N3904 (right) CE Amplifier Bode Phase Plots

We can approximate the poles using the Bode magnitude graphs in Figure 3.2:

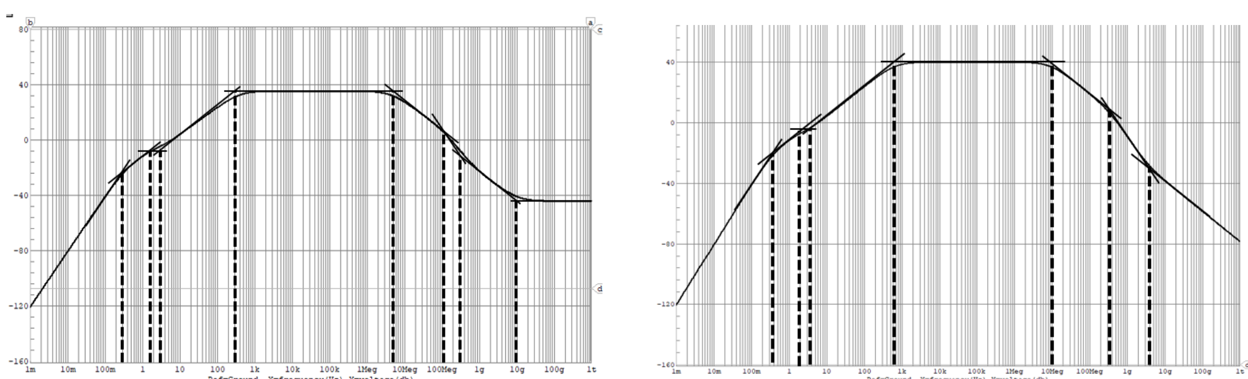

Figure 3.4: 2N4401 (left) and 2N3904 (right) Approximated Poles/Zeros

Transistor	ω_{LP1}	ω_{LP2}	ω_{LP3}	ω_{HP1}	ω_{HP2}	ω_{ZL1-2}	ω_{ZL3}	ω_{ZH1}	ω_{ZH2}
2N4401	0.29Hz	1.69Hz	0.35kHz	98.1MHz	4.89MHz	0	3.11Hz	0.2GHz	9.9GHz
2N3904	0.36Hz	1.73Hz	0.67kHz	278MHz	10.1MHz	0	3.30Hz	3.9GHz	∞

Table 3.1: Simulated and Approximated Poles/Zeros

CALCULATION METHOD:
Now we will calculate the locations of the poles and zeros using Miller's Theorum and OC/SC time constants and compare them to the simulated + approximated poles/zeros.

We will use our small signal model and convert 2N4401 and 2N3904 into equivalent circuits. Calculating C_π and C_μ for our small signal model starting with 2N3904:

$$g_m = \frac{I_C}{V_T} = \frac{0.99mA}{25mV} = \boxed{0.0396} \qquad V_{CB} = V_C \text{ - } V_B = \boxed{4.83\text{V}} \qquad r_\pi = \frac{\beta}{g_m} = \frac{167}{0.0396} = \boxed{4.17\text{k}}$$

$$C_\pi = 2 * CJE + TF * g_m = 2 * 4.5pF + 400pF * 0.0396 = \boxed{24.84\text{pF}}$$

$$C_\mu = \frac{CJC}{(1+\frac{VCB}{VJC})^{MJC}} = \frac{4pF}{(1+\frac{4.83V}{750m})^{330m}} = \boxed{2.06\text{pF}}$$

Applying those values to the small signal model circuit:

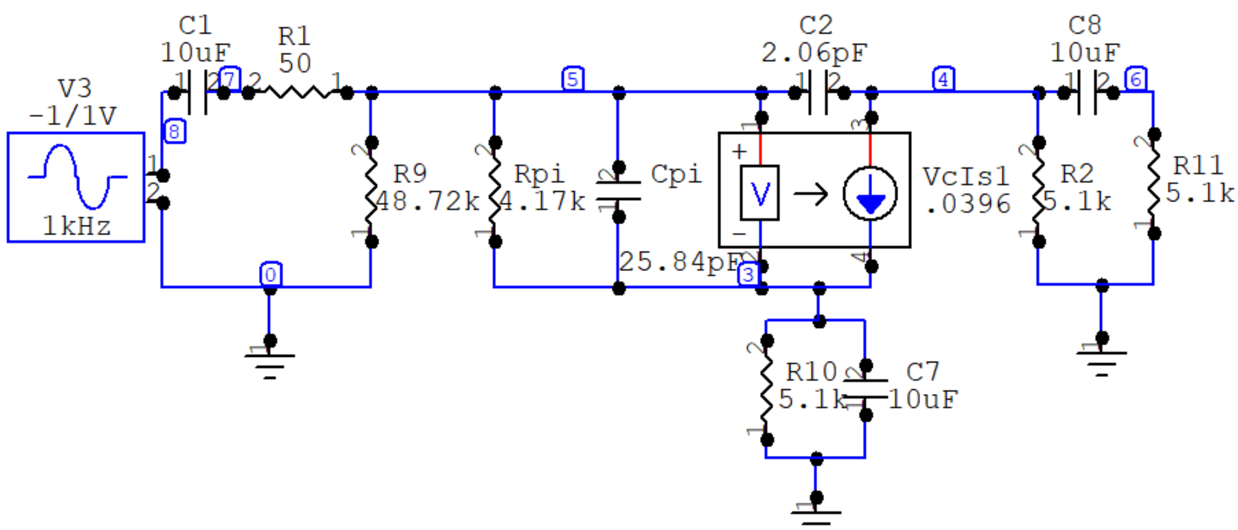

Figure 3.5: Small Signal Model of 2N3904:

Calculating Miller's for the high frequency circuit for 2N3904:

$$k = \boxed{\text{-100}} \qquad C_{\mu 1} = C_\mu * (1-k) = \boxed{208\text{pF}} \qquad C_{\mu 2} = C_\mu * (1 - \frac{1}{k}) = \boxed{2.08\text{pF}}$$

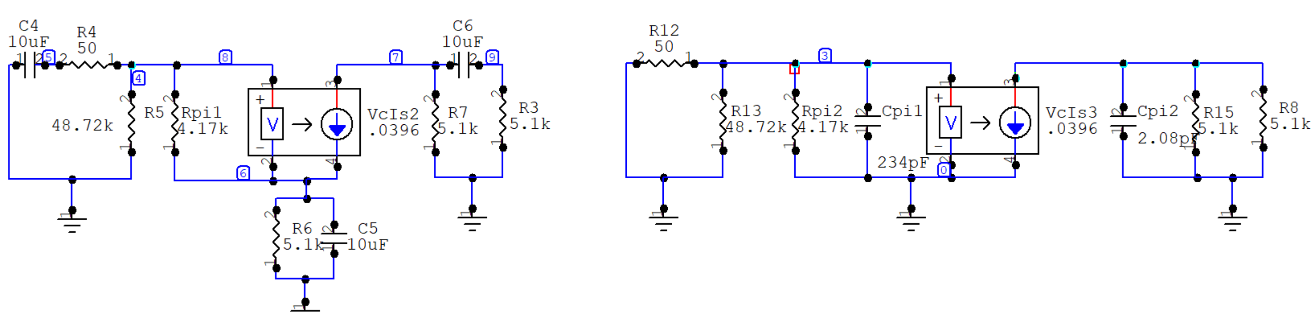

Figure 3.6 Low (left) and High (right) Frequency Small Signal Model:

Calculating Poles from high and low frequency circuits from Figure 3.6

$\omega^{SC}_{LP1} = \frac{2\pi}{10uF*(50+48.72k||(\beta*(4.17k+5.1k)))} = \boxed{0.35\text{Hz}}$ $\omega^{SC}_{HP1} = \frac{1}{2.08pF*5.1k||5.1k} = \boxed{30.01\text{MHz}}$

$\omega^{SC}_{LP2} = \frac{2\pi}{10uF*(10.2k)} = \boxed{1.56\text{Hz}}$ $\omega^{SC}_{HP2} = \frac{1}{234pF*(48.7k||50||4.17k)} = \boxed{13.7\text{MHz}}$

$\omega^{SC}_{LP3} = \frac{2\pi}{10uF*((\frac{50}{\beta}||\frac{48.7k}{\beta}+\frac{4.17k}{\beta})||5.1k))} = \boxed{632.96\text{Hz}}$

Zeros from high and low frequency circuits from Figure 3.6:

$\omega_{LZ1} = \frac{2\pi}{5.1k*10uF} = \boxed{3.12\text{Hz}}$ With two zeros at 0 and one at ∞

We will now preform the same series of calculations for 2N4401:

$g_m = \frac{I_C}{V_T} = \frac{0.99mA}{25mV} = \boxed{0.0396}$ $V_{CB} = V_C$ - $V_B = \boxed{4.17\text{V}}$ $r_\pi = \frac{\beta}{g_m} = \frac{167}{0.0396} = \boxed{4.17\text{k}}$

$$C_\pi = 2*CJE + TF*g_m = 2*23.4pF + 512pF*0.0396 = \boxed{67.08\text{pF}}$$

$$C_\mu = \frac{CJC}{(1+\frac{V_{CB}}{VJC})^{MJC}} = \frac{10.2pF}{(1+\frac{4.17V}{750m})^{330m}} = \boxed{5.48\text{pF}}$$

$k = \boxed{-100}$ $C_{\mu 1} = C_\mu*(1-k) = \boxed{553\text{pF}}$ $C_{\mu 2} = C_\mu*(1-\frac{1}{k}) = \boxed{5.53\text{pF}}$

$\omega^{SC}_{LP1} = \frac{2\pi}{10uF*(50+48.72k||(\beta*(4.17k+5.1k)))} = \boxed{0.35\text{Hz}}$ $\omega^{SC}_{HP1} = \frac{1}{5.53pF*5.1k||5.1k} = \boxed{11.29\text{MHz}}$

$\omega^{SC}_{LP2} = \frac{2\pi}{10uF*(10.2k)} = \boxed{1.56\text{Hz}}$ $\omega^{SC}_{HP2} = \frac{1}{589pF*(48.7k||50||4.17k)} = \boxed{5.47\text{MHz}}$

$\omega^{SC}_{LP3} = \frac{2\pi}{10uF*((\frac{50}{\beta}||\frac{48.7k}{\beta}+\frac{4.17k}{\beta})||5.1k))} = \boxed{632.96\text{Hz}}$

$\omega_{LZ1} = \frac{2\pi}{5.1k*10uF} = \boxed{3.12\text{Hz}}$ With two zeros at 0 and one at ∞

Below is the calculated (C) and approximated poles (A):

Transistor	ω_{LP1}	ω_{LP2}	ω_{LP3}	ω_{HP1}	ω_{HP2}	ω_{ZL1-2}	ω_{ZL3}	ω_{ZH1}	ω_{ZH2}
2N4401(C)	0.35Hz	1.56Hz	0.63kHz	11.3MHz	5.47MHz	0	3.12Hz	∞	∞
2N3904(C)	0.35Hz	1.56Hz	0.63kHz	30.0MHz	13.7MHz	0	3.12Hz	∞	∞
2N4401(A)	0.29Hz	1.69Hz	0.35kHz	98.1MHz	4.89MHz	0	3.11Hz	0.2GHz	9.9GHz
2N3904(A)	0.36Hz	1.73Hz	0.67kHz	278MHz	10.1MHz	0	3.30Hz	3.9GHz	∞

Table 3.2: Calculated (C) vs Approximated (A) Poles/Zeros

We see that the estimation is generally fairly close to the approximation, but breaks down in the high frequency. This is likely due to the close proximity of the poles. I used a linear approximation method, and generally the closer the calculated poles the less accurate the simulation + simulation is. We also get real zero values when we approximate versus our more undefined calculated values.

3.b Locating When Our Amplifier Goes Non-Liner

A circuit will start to become non-linear near it's 3dB frequency. I will use a midband frequency of 1kHz and peak of 100mV. We see both transistors go non-linear after around 65uV.

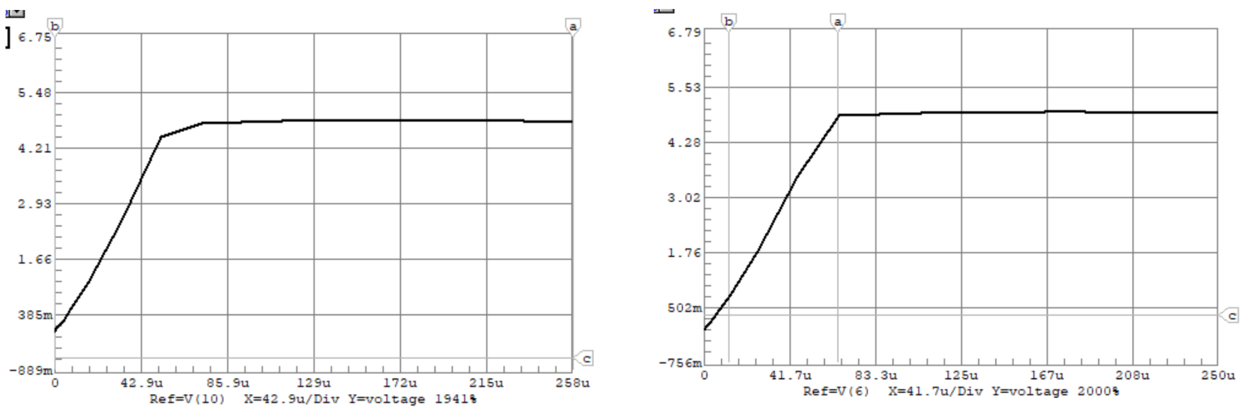

Figure 3.7: 2N4401 (left) and 2N3904 (right) Approximated Poles/Zeros

3.c Input/Output Impedance at Midband

Solving and simulating for input and output impedance:

$$Z_{input} = R_{BB}||r_{pi} \qquad Z_{output} = R_C$$

Method	Z_{input} (2N4401)	Z_{Output} (2N4401)	Z_{input} (2N3904)	Z_{Output} (2N3904)
Simulated	$3.8k\Omega$	$5.1k\Omega$	$3.8k\Omega$	$5.1k\Omega$
Calculated	$3.8k\Omega$	$5.1k\Omega$	$3.8k\Omega$	$5.1k\Omega$

Table 3.3: Input/Output Impedance: Simualted+Approx and Calculated

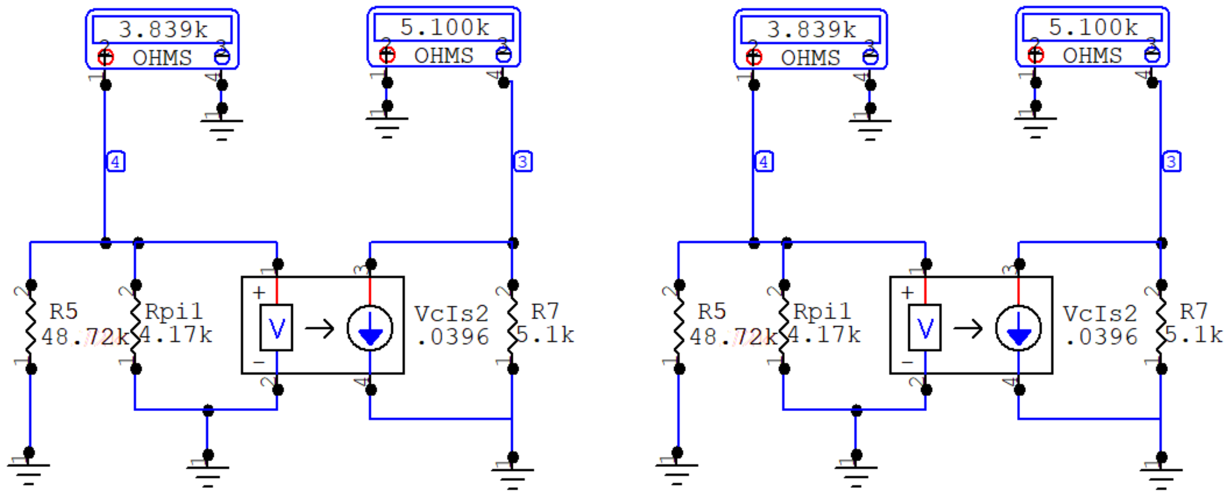

Figure 3.8: 2N4401 (left) and 2N3904 (right) Simulated Input/Output Impedance

3.d Selecting a Transistor

Both transistors are extremely similar. One of the differences are the pole locations. And, given that 2N3904 has a larger midband range I would pick it for more applications over 2N4401.

4 Part III: The Common Base (CB) Amplifier

4.a Calculating vs Approximation Methods: Comparing Poles/Zeros

APPROXIMATION METHOD:

We will now simulate and approximate 2N3904.

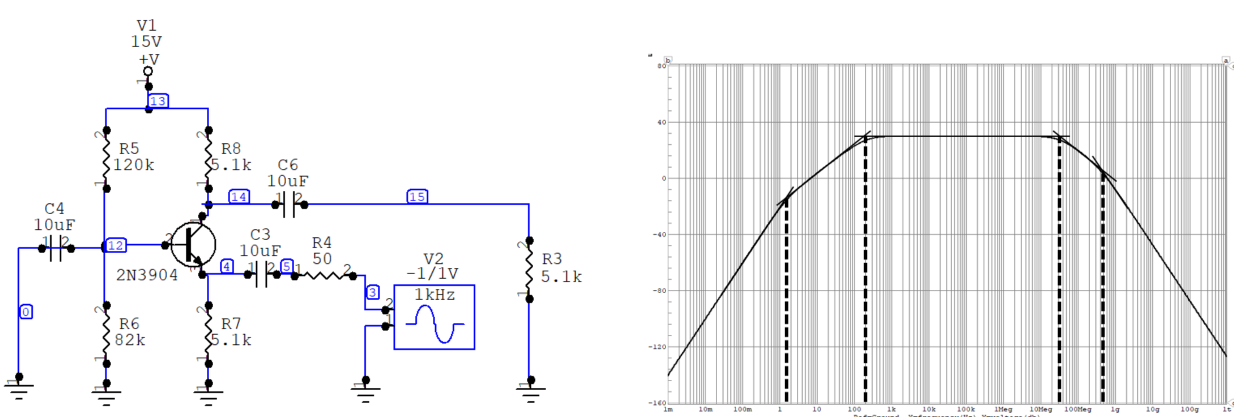

Figure 4.1: 2N3904 BE Amplifier and Corresponding Bode Response

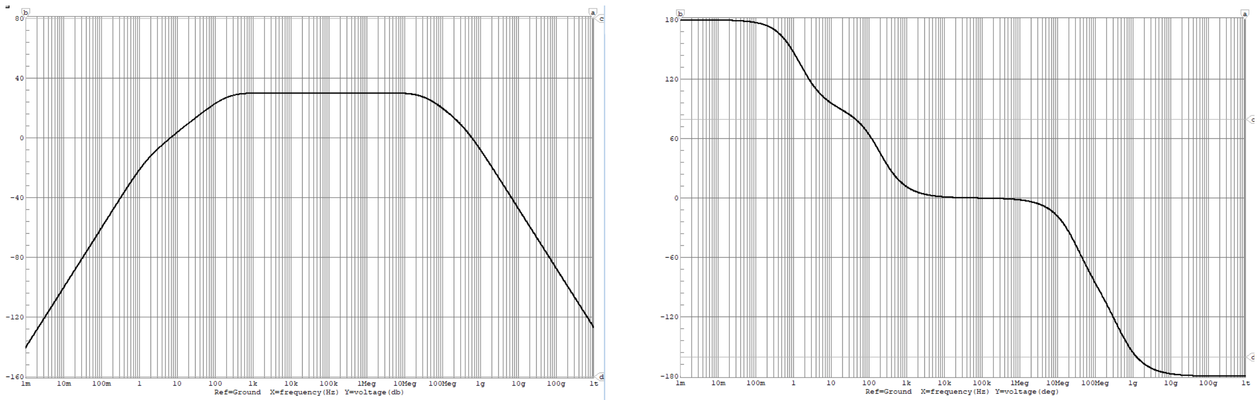

Figure 4.2: Bode Magnitude and Phase Responses

Transistor	ω_{LP1}	ω_{LP2}	ω_{HP1}	ω_{HP2}	ω_{ZL1}	ω_{ZH1}
2N3904	1.59Hz	171Hz	22.1MHz	30.6MHz	0	∞

Table 4.1: Simulated and Approximated Poles/Zeros

CALCULATION METHOD:

Now we will calculate the locations of the poles and zeros using Miller's Theorum and OC/SC time constants and compare them to the simulated + approximated poles/zeros. We will use the small signal model values we found in 3.a to derive a circuit.

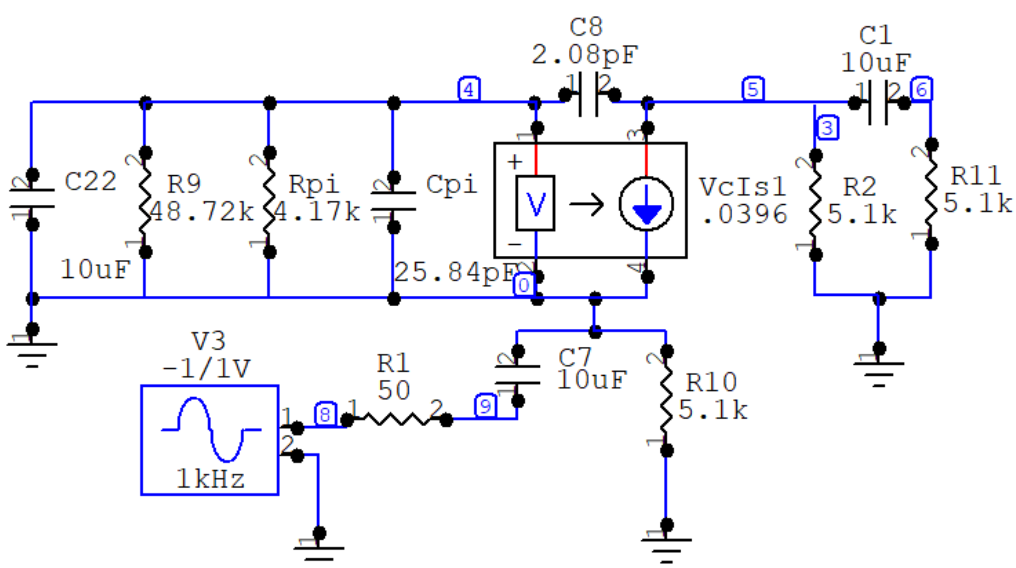

Figure 4.3: Small Signal Model of 2N3904

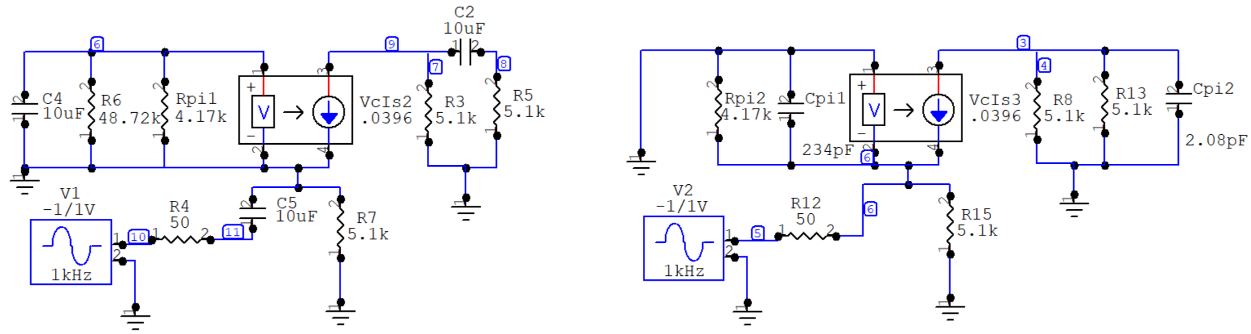

Figure 4.4: Low (left) and High (right) Frequency Small Signal Model

Calculating Poles from high and low frequency circuits from Figure 4.4

$$\omega_{LP1}^{SC} = \frac{2\pi}{10uF*(48.72k||(4.17k+\beta*5.1k))} = \boxed{0.46\text{Hz}}$$

$$\omega_{LP2}^{SC} = \frac{2\pi}{10uF*(10.2k)} = \boxed{1.56\text{Hz}}$$

$$\omega_{LP3}^{SC} = \frac{2\pi}{10uF*(\frac{4.17k}{\beta}+50)} = \boxed{211.87\text{Hz}}$$

$$\omega_{LZ2}^{SC} = \frac{2\pi}{10uF*48.72k} = \boxed{0.33\text{Hz}}$$

$$R_{test} = \frac{1}{r\pi} = \frac{2}{10k||50} = 24.72\Omega$$

$$\omega_{HP1}^{SC} = \frac{1}{R_{test}C} = \frac{1}{24.72*10pF} = \boxed{27.5\text{MHz}}$$

$$\omega_{HP2}^{SC} = \frac{1}{2pF*5k} = \boxed{30.6\text{MHz}}$$

Transistor	ω_{LP1}	ω_{LP2}	ω_{LP3}	ω_{HP1}	ω_{HP2}	ω_{ZL1}	ω_{ZL2}	ω_{ZH1}
2N3904	0.46Hz	1.56Hz	211.87Hz	27.1MHz	439MHz	0	0.3	∞

Table 4.2: Calculated Poles/Zeros

This is a very interesting result. We see that our calculated poles are very different compared to the poles we simulated and estimated. The extra pole/zero pair that we didn't anticipate are very close to each other, thus cancel out in the Bode plot. Additionally our estimates on the graph are off and our poles are actually calculated to be very close to each other. This is because the method of estimating we used, linear extrapolating, works poorly when poles are close together.

4.b Locating When Our Amplifier Goes Non-Liner

A circuit will start to become non-linear near it's 3dB frequency. I will use a midband frequency of 1kHz and peak of 1V. We see both transistors go non-linear after around 50uV.

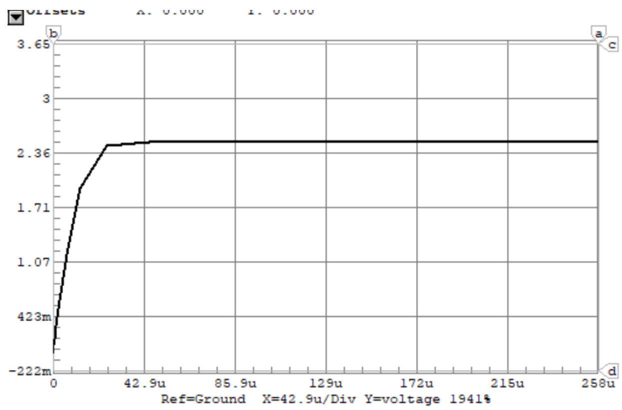

Figure 4.3: 2N3904 Going Non-Linear

4.c Input/Output Impedance at Midband

$$Z_{input} = R_{BB}||r_{pi} \qquad Z_{output} = R_C$$

Method	Z_{input}	Z_{Output}
Simulated	24.88Ω	$5.1k\Omega$
Calculated	24.72Ω	$5.1k\Omega$

Table 3.3: Input/Output Impedance: Simualted+Approx and Calculated

5 Conclusion

After analyzing different methods and measuring/simulating the behaviour of transistors we can see that our estimation methods such as the 1/3 rule and the small-signal model approximations work very well and can be used to attain accurate results.

6 Appendix

References

[1] $https://www.mouser.ca/datasheet/2/389/CD00003223-491114.pdf$

[2] $https://www.youtube.com/watch?v=OrsAtjiChLkab_channel=SalimKoteish$

[3] $https://www.youtube.com/watch?v=F_97vyRhyl8ab_channel=SimulateElectronics$

[4] $https://www.youtube.com/watch?v=y2eenHbFiF8ab_channel=APDahlen$

[5] $https://www.cxi1.co.uk/ltspice/dccircuits.htm$